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Simulated Measurement of the D_s Meson Semileptonic Decay Form Factor with the $\bar{\text{P}}$ANDA Detector

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Abstract

We simulate the anti-proton and proton interaction to evaluate the $\bar{\text{P}}$ANDA detector performance in the measurement of the semileptonic decay form factor of $D_s^+ \to e^+\nu_e\eta$. The kinematics of the neutrino have been reconstructed with a complete simulation model of the detector and reconstruction tools. With theoretical predictions of the cross section, we obtain a preliminary estimate of the expected count rate for the future data taking.

Keywords: transition form factor, open charm, semileptonic decay, simulation analysis

1. Introduction

The $\bar{\text{P}}$ANDA experiment [1] is one of the major projects on the Facility for Antiproton and Ion Research (FAIR) in Darmstadt of Germany. It will study the interactions between an intense, phase space cooled beam of antiprotons provided by the High Energy Storage Ring (HESR) and hydrogen or heavier nuclear targets in the momentum range of 1.5-15 GeV/c. In order to serve the wide physics potential with antiprotons, $\bar{\text{P}}$ANDA is designed as a general purpose detector covering nearly the complete solid angle for both neutral and charged particles with good momentum and particle identification capabilities as well as an excellent vertex determination. By performing resonance and threshold scans with the high precision anti-proton beams in a momentum spread down to a few times 10^{-5}, $\bar{\text{P}}$ANDA will achieve more than an order of magnitude higher mass resolution compared to existing facilities, e.g. the B-factories.

The semileptonic D_s decays are governed by both weak and strong interactions. The strong interaction dynamics can be described by a single form factor $f_+(q^2)$, where q^2 is the invariant mass of the lepton-neutrino system. The decay rate can be written as

$$\frac{d\Gamma(D_s^+ \to e^+\nu_e\eta)}{dq^2} = \frac{G_F^2}{24\pi^3}\,|V_{cs}|^2\,p_\eta^3\left|f_+(q^2)\right|^2, \qquad (1)$$

where G_F is the Fermi constant, p_η is the magnitude of the three-momentum of the η in the D_s^+ rest frame, and $|V_{cs}|$ is the relevant Cabibbo-Kobayashi-Maskawa matrix element. Via measuring the decay rate, and taking the widely accepted value of $|V_{cs}|$ from PDG [2], the form factor $\left|f_+(q^2)\right|^2$ can be extracted experimentally. Theoretical calculations of the form factor offer increasing precision such as the recent results from lattice quantum chromodynamics [3] and light-cone sum rule [4]. Therefore, the experimental validation of the results becomes important.

Recent data from CLEO on semileptonic $D \to \pi, K$ decays [5, 6] have been used for more accurate determinations of the CKM matrix elements $|V_{cd}|$ and $|V_{cs}|$ [7], and the case is sometimes extended to the η and η' in the final state. The principal difference is that now gluonic contributions enter that couple to the singlet component of the η and η', and the mass corrections are more important due to the larger strange quark mass. The theoretical uncertainty to the ratio of the branching ratios $\mathcal{B}(D_s^+ \to e^+\nu_e\eta')/\mathcal{B}(D_s^+ \to e^+\nu_e\eta)$ is dominated by the

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uncertainty of the gluonic contribution [8], thus an improvement of the relative branching ratio can help to fix it [9].

We present here an improved and updated version of our previous simulation [10]. The goal of the continuous study is to evaluate and optimize the physics performance of the P̄ANDA detector to measure the form factor of semileptonic D_s meson decays. In the following sections, we will introduce the reconstruction strategies and updated results on resolutions. The expected event rate is estimated by using the reconstruction efficiency presented here and a theoretical estimate of the production cross section is made.

2. Reconstruction of the decay chain

The official offline simulation framework available to the collaboration is called PandaRoot [11]. About the reconstruction procedure, we focus here on software development and on the evaluation of the expected precision of these measurements of the P̄ANDA detector. The following decay channels have been simulated with 10,000 events at $\sqrt{s} = 4.108$ GeV: $\bar{p}p \to D_s^+ D_s^-$; $D_s^- \to K^+K^-\pi^-$; $D_s^+ \to e^+\nu_e\eta$; $\eta \to \pi^+\pi^-\pi^0$; $\pi^0 \to \gamma\gamma$. The related decay models for each channel have been studied in a previous work [10]. We simulate the particle tracking through the complete P̄ANDA detector by using the GEANT4 transport code [12].

To reconstruct D_s^-, we perform the vertex fitting and mass constraint fitting for $(K^+K^-\pi^-)$ combination, where the cut applied on the probability distribution from the χ^2 values is $prob > 0.01$. The reconstruction strategy is slightly complicated for the semileptonic decay chain: $D_s^+ \to e^+\nu_e\eta$, $\eta \to \pi^+\pi^-\pi^0$ and $\pi^0 \to \gamma\gamma$. We started from the combination of two photons detected by the Electromagnetic Calorimeter (EMC). The photon energy threshold is set to $E_\gamma \geqslant 30$ MeV to reduce the photon multiplicity due to bump split off and bremsstrahlung. The mass constraint fitting has been performed on the two-photon system to select the "best" fitted π^0 for reconstructing the mother η. The π^+ and π^- tracks allow the reconstruction of $\eta \to \pi^+\pi^-\pi^0$. The reconstructed η candidates are selected with a χ^2 probability cut on the mass constraint fit of the three-pion system.

After reconstructing the intermediate particles D_s^- and η, the kinematics of the undetected neutrino can be calculated based on a four-momentum condition as

$$M_{\nu_e}^2 = \left(E_{\bar{p}p} - E_{D_s^-} - E_\eta - E_{e^+}\right)^2 - \left|\mathbf{p}_{\bar{p}p} - \mathbf{p}_{D_s^-} - \mathbf{p}_\eta - \mathbf{p}_{e^+}\right|^2, \tag{2}$$

where $E_{\bar{p}p}(\mathbf{p}_{\bar{p}p})$ is the energy (three-momentum) of the initial anti-proton beam and proton target system.

3. Resolution and count rate

With the present software, we reconstruct the decay chain with an efficiency of $\epsilon(D_s^-) = 17\%$ and $\epsilon(\eta) = 11\%$. Table 1 summarizes the preliminary results for the reconstructed mass resolutions for D_s^- and η.

Table 1: Reconstruction results of D_s^- and η. σ_{mass} is the mass resolution; σ_{vtx} is the vertex resolution and σ_{mom} is the relative resolution of momentum $\Delta p/p^{MC}$.

	σ_{mass}	σ_{vtx} [μm]			σ_{mom} [%]	
	[GeV/c^2]	x	y	z	p_t	p_z
D_s^-	0.0155	67	63	144	2.9	1.3
η	0.0109	294	273	790	2.0	1.5

The reconstructed ν_e has a mass resolution of 0.009 GeV/c^2. In Fig.1, we show that 41% of the ν_e candidates are inside the mass window (yellow) $\left|M_{\nu_e}^2\right| < 0.1$ GeV^2/c^4. For the lepton-neutrino system, we obtain $\epsilon(e^+\nu_e) = 2\%$ and the invariant mass squared distributions are shown by Fig.2. Note that the maximum $M^2(e^+\nu_e)$ is consistent with the physical limitation $q^2 \leq (M_{D_s} - M_\eta)^2 \approx 2.02$ GeV^2/c^4.

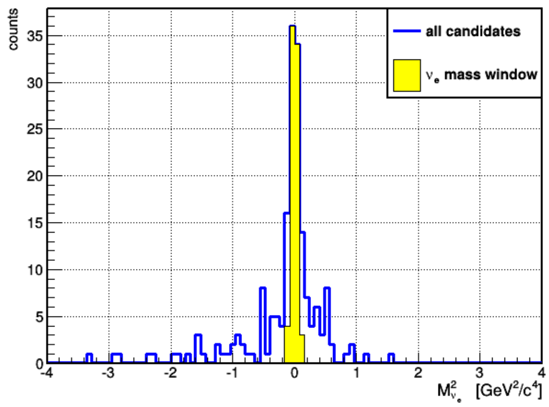

Figure 1: Mass squared of ν_e candidates $M_{\nu_e}^2$ given by Eq.2. The mass window is $\left|M_{\nu_e}^2\right| < 0.1$ GeV^2/c^4.

The theoretical approaches and models suggest a wide range of estimates on the cross section of charm production in proton-antiproton interaction; e.g. for the cross section of $p\bar{p} \to \bar{D}^0 D^0$, the estimates in Ref.[13] using the double handbag approach is two orders larger than the prediction coming from the quark-gluon string

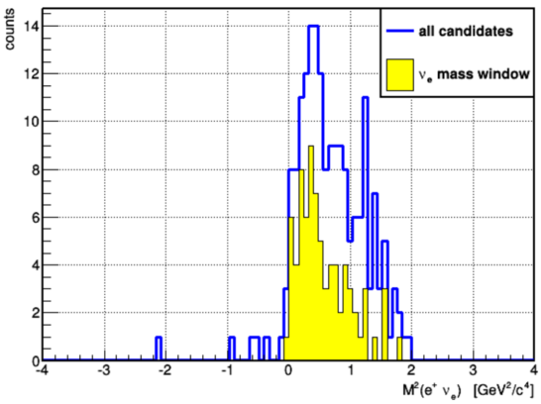

Figure 2: Invariant mass squared of lepton-neutrino system $M^2(\nu_e e^+)$. The mass window of neutrino is same within Fig.1 $\left|M^2_{\nu_e}\right| < 0.1$ GeV^2/c^4.

model indicated by Ref.[14]. Assuming the cross section on the production of a D_s pair at $\bar{\text{P}}$ANDA will be 20 *nb* for a beam momentum of 8 GeV/c [15], we estimate the production rate to be approximately 100 events per month for a luminosity of 2×10^{32} cm^{-2}s^{-1} and the average branching ratios $\mathcal{B}(D_s^+ \to \eta e^+ \nu_e) = 2.67\%$ and $\mathcal{B}(D_s^- \to K^+ K^- \pi^-) = 5.49\%$ [2].

4. Summary

The hadronic decay $D_s \to KK\pi$ and the decay $\eta \to \pi^+\pi^-\pi^0$ from the semileptonic decay $D_s^+ \to e^+\nu_e\eta$ have been investigated within the PandaRoot framework in order to estimate the resolutions and efficiencies. We also expanded our study on the kinematics study to the unmeasured neutrino, which was not included in our previous work [10]. Comparing with our previous results, the reconstruction resolution has been improved due to improvements of software in particularly on the kinematic fitter.

The count rate of useful events to measure with $\bar{\text{P}}$ANDA the semileptonic decay form factor has been estimated to be 100 events per month. We expect significant improvements since our simulation and reconstruction tools are still in development. The upcoming steps will include a modification of the present software to improve the reconstruction efficiency and an investigation of the background channels.

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